# Research on Asphalt Pavement FWD Deflection Synthetic Correction Coefficient

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ABSTRACT: Deflection was adopted as control criteria in asphalt pavement construction quality management in China. Static parameters and Burmister layered system were used to calculate deflection in existing design procedure, but the difference between the deflections calculated from this way and deflections measured from FWD could reach 50%. This study introduced a deflection synthetic correction coefficient, F, to shorten the difference gap. Through Deflections collected from indoor and in-field full scale test sections combined with test roads in six freeways, meanwhile, ABAQUS was used to create three dimension finite element module to simulate the response of test sections and calculate their deflections under moving vehicle loads, then comparison was conducted between deflections measured by FWD and deflections calculated from ABAQUS. Finally, the grey entropy theory was utilized to determine the influence factors which are prepared for constructing the formula of F. The study concluded that the difference between calculated deflection after correction and deflection measured in field decreased to 30%, which enhanced the precision of management of construction quality through surface deflection, and an encouraging way to judge the reasonability of deflection measured by FWD.

KEY WORDS: Asphalt pavement, falling weight deflectometer, finite element method, grey entropy method, deflection synthetic correction coefficient

## 1 INTRODUCTION

As an indicator of stiffness or integrity of pavement, deflection measurement is a simple, fast, economic, nondestructive way to evaluate pavement structure (Yao, 2001). Referred to research of Soviet Union(Ivanov et al., 1956), since the first edition of flexible pavement design guide until the latest edition, deflection was adopted as the most important design control indicator in China (Yao, 2001). However, usually there was difference between deflection calculated from elastic layered system and measured one, sometimes it could reach 50%. To conciliate this difference, the deflection synthetic correction coefficient was introduced, which denoted as measured deflection divided by theoretically calculated deflection.

Hu et al. studied the singularity of the deflection synthetic correction coefficient that the design thickness of asphalt layer increased with the increasing of subgrade modulus (Hu et al, 2005). In Gao's analysis (Gao et al, 2003), the main cause of difference between theoretically calculated deflection and in field measurements was the mismatch between static modulus in current design guide in china and modulus under moving vehicle load. Dong et. al built a new deflection synthetic correction coefficient by introducing FWD deflection basin parameters (both area and slope rate) (Dong, 2011).

In effect, deflection served as a design control was only a practice of China, other design guides worldwide rather refine characterization of the materials than modify the deflection directly to reduce that difference. ( Dunlap et al, 1963; Monismith et al,1963, Uzan, 1985). Moreover, a lot of efforts were extended to deflection temperature correction. Chen et al built a model to adjust deflection at different temperature to a reference temperature, and conclusions were drawn that deflection temperature correction factor was related to thickness of asphalt layer, and location dependent but site dependent (Chen, et al, 2000). Lukanen calibrated the BELLS model with new data base, and analyzed the influence of temperature on deflection, deflection basin shape factors, moduli of pavement materials (Lukanen et al, 2000).

As the wide spreading of FWD in China, FWD was included as standard deflection measure device. To adjust to the new design system and new deflection test device, a new deflection synthetic correction coefficient is needed.

The objective of this paper is, by paving test section in laboratory and in field, testing modulus of asphalt mixture and chemical treated material in laboratory, back-calculating of subgrade modulus through ABAQUS computer program, deflection testing in these two test sections, collecting history deflection data from 6 freeways, to build a new form of deflection synthetic correction coefficient and verify it by deflection collected in those freeways.

## 2 DEFLECTION COLLECTING

### 2.1 Data Collection in Test Section

A 12m in length, 3m in width and 2m in depth test section was paved in laboratory. In-field test section was paved as 20 meters in length, 6 meters in width. Table1 shows the structures and materials of these test sections.

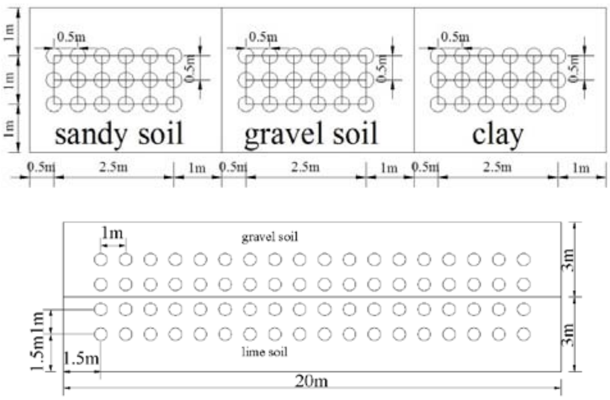
Table1: Structures and Materials of Sections

| Section number / Structure | Laboratory | | | In-Field | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | L-1 | L-2 | L-3 | I-1 | I-2 | I-3 | I-4 | I-5 | I-6 | I-7 | I-8 |
| | Materials | Materials | Materials | Materials | Materials | Materials | Materials | Materials | Materials | Materials | Materials |
| Wearing course | SMA-13 (5cm) | SMA-13 (5cm) | SMA-13 (5cm) | SMA-13 (6cm) | SMA-13 (6cm) | SMA-13 (8cm) | SMA-13 (4cm) | SMA-13 (6cm) | SMA-13 (6cm) | SMA-13 (8cm) | SMA-13 (4cm) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Binder course1 | AC-16 (10cm) | AC-16 (10cm) | AC-16 (10cm) | AC-16 (5cm) | AC-16 (10cm) | AC-16 (12cm) | AC-16 (12cm) | AC-16 (5cm) | AC-16 (10cm) | AC-16 12cm) | AC-16 (12cm) |
| Binder course2 | AC-20 (20cm) | AC-20 (20cm) | AC-20 (20cm) | CTG (28cm) | CTG (25cm) | CTG (15cm) | AC-20 (15cm) | CTG (28cm) | CTG (25cm) | GA (15cm) | AC-20 (15cm) |
| Subbase | CTG (20cm) | CTG (20cm) | CTG (20cm) | GA (18cm) | GA (18cm) | GA (18cm) | GA (15cm) | GA (18cm) | GA (18cm) | GA (18cm) | GA (15cm) |
| Subgrade | GS[a] | Clay[a] | WS[a] | LTS[b] | LTS[b] | LTS[b] | LTS[b] | GS[b] | GS[b] | GS[b] | GS[b] |

SMA-13-Stone matrix asphalt mixtures with normal maximum aggregate size 13mm; AC-16-asphalt concrete with normal maximum aggregate size of 16mm and AC-20-asphalt concrete with normal maximum aggregate size of 20mm. CTG-cement treated gravel; LTS-lime treated soil; GS-Gravel soil; WS-wheathered shale soil. a: The thickness of subgrade was 1.45m, under which is a rigid layer; b: both the depth of lime treated soil and gravel soil were 1m, below which is the original subgrade.

Deflection was tested after each layer was paved in the process of construction, in order to analyze the relationship between temperature and deflection, air temperature and surface temperature and temperature profile of asphalt layers were recorded. 54 test points were located in laboratory test section, 18 for each kind of subgrade soil; Figure1a) shows the layout of the test point. Similarly, 72 test points were located in in field test section, which were arranged into 4 rows, 36 points for each kind of subgrade soil; Figure1b) shows the configuration of the test point at in-field test section.




a) Laboratory test point layout

b) In-field test point layout

Figure1: Schematic of test point in laboratory and in-field test section

## 2.2 History data collecting

For the purpose of verification, geometric data, materials, measured deflection of six freeways in China with good serviceability were collected. They are G5001 in Chongqing, G25, G22-JL, G22-ML, G15, and G2001 in Shandong.

## 2.3 Determination of Material Modulus

To determine the dynamic modulus of asphalt concrete, the SPT (Simple Performance Test) produced by Australia Industrial Process Controls Ltd was used. The test samples of AC-20(asphalt concrete with nominal maximum aggregate size of 20mm) were cored from test section, and test samples of AC-16 (asphalt concrete with nominal maximum aggregate size of 16mm) and SMA-13 were prepared by superpave gyratory compactor. Table2 shows the test results of dynamic modulus.

Table2: Dynamic Moduli of Asphalt Concrete on Test Section under Different Temperature

| Materials | Modulus(MPa) | | | | | |
|---|---|---|---|---|---|---|
| | 5°C | 10°C | 20°C | 30°C | 40°C | 50°C |
| SMA-13(L) | 12471.3 | 10620.5 | 7044.6 | 5571.4 | 2501.9 | 1305.2 |
| SMA-13(I) | 10138.2 | 8393.7 | 5300.3 | 4070.4 | 2449.8 | 1317.9 |
| AC-16(L) | 11466.3 | 9744.9 | 6245.6 | 4931.5 | 2245.9 | 1215.8 |
| AC-16(I) | 9523.2 | 7889.2 | 4914.4 | 3631.7 | 2164.5 | 1218.9 |
| AC-20(L) | 17339 | 14270 | 7844 | 5568 | 3255 | 1616 |
| AC-20(I) | 15412 | 12148 | 6733 | 4952 | 2955 | 1325 |

Note: the L in the bracket refers to material used in laboratory; and I is materials used in in-field.

The dynamic moduli of chemical treated materials were tested by the same method as asphalt mixture. The average modulus of upper base material in laboratory, lower base material of laboratory, base material in field were 15538 MPa, 13315 MPa and 10652 MPa, respectively.

Due to lack of cohesiveness, it is very hard to prepare sample for modulus test, the modulus of graded aggregate obtained by referring to Ling's research (Ling et al, 2010). The modulus of a certain material was found to vary with its location, for graded aggregate as base and subbase the modulus was 350 MPa and 220 MPa, respectively.

Referred to NCHRP1-28A (Witczak, 2003), the $k_i$s model was used in this paper to predict the dynamic modulus of subgrade. To determine the value of $k_i$s, the formula calibrated by Li was involved in this paper (Li et. al, 2003):

$$k_1 = -0.0960w + 0.3929\rho_d + 0.0142I_P + 0.0109P_{0.075} + 1.0100 \quad (1)$$

$$k_2 = -0.0005w - 0.0069I_P - 0.0026P_{0.075} + 0.6984 \quad (2)$$

$$k_3 = -0.2180w - 3.0253\rho_d - 0.0323I_P + 7.1474 \quad (3)$$

Where: $w$—moisture(%); $p_a$ —standard air pressure, 100kPa; IP—index of plasticity (%); $\rho_d$—dry density(g/cm3); $P_{0.075}$—the passing percentage of 0.075 sieve(%).

The physical property parameter in equation (2), (3), (4) were tested in this study, which enabled the conduction of calculation of $k_i$s, Table2 shows the calculated results.

Table2: $k_i$s of different type of soil

| $k_i$ | Shale soil | Clay | Gravel soil(with 55% gravel) | Lime treated soil | Gravel soil(33% gravel) |
|---|---|---|---|---|---|
| $k_1$ | 1.189 | 1.087 | 1.407 | 1.968 | 1.303 |

| | | | | | |
|---|---|---|---|---|---|
| $k_2$ | 0.609 | 0.545 | 0.603 | 0.288 | 0.560 |
| $k_3$ | -1.072 | -1.904 | -1.412 | -0.881 | -1.659 |

According to Witczak's $k_i$s model, to predict the modulus of subgrade, the equivalent stress level should be determined. Based on the principle of deflection equivalent, through analyzing stress distribution of pavement under FWD impact load by three dimension nonlinear finite element program ABAQUS and deflection iterative back-calculating, the equivalent modulus of subgrade could be predicted. In the process of iteration, UMAT in ABAQUS was used to develop subroutine for constitutive model of subgrade material. Besides, the deflection at the top of the subgrade was selected as benchmark in the nonlinear subroutine, the modulus of the subgrade was adjusted to match the deflection, once the difference between the deflection calculated and the benchmark is allowable, then the modulus is the equivalent modulus of the nonlinear layer.

## 3 KEY FACTORS OF DEFLECTION SYNTHETIC CORRECTION COEFFICIENT

One of the most important causes of the difference between theoretically calculated deflection and measurements is the nonlinearity of the subgrade; therefore, in constructing the formula of deflection synthetic correction coefficient, denoted as F, the nonlinearity is a major consideration. In the latest asphalt pavement design guide of China, the modulus of subgrade ($E_0$) and deflection measured in-field ($l_s$) are included as independent in the formula of F. As matter of fact, the magnitude of $l_s$ is determined by $E_0$, in Hu's research, $l_s$ contribute greatly to the occurrence of singularity that the design thickness of asphalt layer increases as the modulus of subgrade increasing (Hu, 2005). So, in this paper, the $l_s$ is replaced by another independent. The independents that are took in consideration in this paper are E0, ratio of surface layer and base $E_{x1}/E_{x2}$, curving stiffness ratio of surface layer and base $D_1/D_2$, the thickness of asphalt layer h, total thickness of pavement $H$.

In effect, pavement is a multi-layer system, to ease analysis, certain layers with same kind of material need to convert into one equivalent layer, therefore, the equivalent modulus and thickness of these layers should be determined. In this paper, $E_{x1}$ and $E_{x2}$ are equivalent modulus of surface layer and base, respectively, which could calculate by equation (5). $D_1$ and $D_2$ are equivalent curving stiffness of surface layer and base, respectively, which could calculate by equation (6) (Tan, 2001).

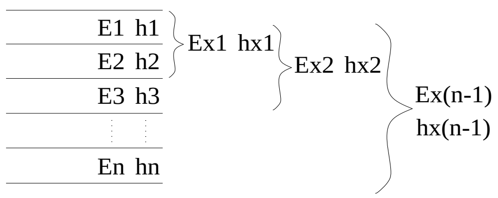



Figure 2: Schematic of equivalent modulus Calculation

$$E_{Xi} = \frac{h_i^{\ 2} E_i + h_{i+1}^{\ \ \ 2} E_{i+1}}{h_i^{\ 2} + h_{i+1}^{\ \ \ 2}} \qquad (i=1,2\ldots\text{n-1}) \tag{5}$$

$$h_{Xi} = \left( \frac{12 D_{Xi}}{E_{Xi}} \right)^{1/3} (i=1,2\ldots\text{n-1}),\quad D_{Xi} = \frac{E_i h_i^3 + E_{i+1} h_{i+1}^3}{12} + \frac{(h_i + h_{i+1})^2}{4} \left( \frac{1}{E_i h_i} + \frac{1}{E_{i+1} h_{i+1}} \right)^{-1} \tag{6}$$

Where: $E_{Xi}$, equivalent modulus of layers; $D_{Xi}$, equivalent stiffness $h_{Xi}$, equivalent layer thickness.

To determine the key influence factors of F, the grey theory is introduced in this paper. Grey theory is an engineering system theory advanced by Deng (Deng, 1993). By this theory, the major influence factors could be determined when information is limited. Grey entropy method, a brand of grey system, is used in this analysis to select the independents for the construction of F. When conducting grey entropy analysis, F is selected as the evaluating indicator to determine the influence of the six factors stated above. Figure 3 shows the result of grey entropy analysis.

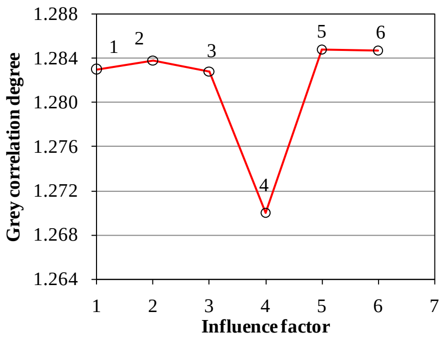



Figure3: grey correlation degree vs. influence factor

As Figure3 shows the influence factors could arrange in order, from the largest to smallest are: $H$, $l_s$, $h$, $E_0$, $E_1/E_2$, $D_1/D_2$. Modulus of subgrade is the major influence of difference between theoretically calculated deflection and deflection measured in field. Take $E_0$ as judge criteria, then influence on F greater than $E_0$ could accept as a key influence factor. As stated above, ls should be replaced to eliminate singularity, and then the key factors are total thickness of pavement, H; modulus of subgrade, $E_0$; ratio of modulus of surface layer and base, $E_1/E_2$. For the reason that pavement is a multi-layered system, pavement should be divided into several layers, in this paper, pavement was divided into subgrade, base and surface. Then the total thickness of pavement ($H$) could be represented by the equivalent thickness of the pavement ($h_x$).

## 4 CONSTURCTION OF F FORMULA

The subgrade in laboratory test section is free from effect of moisture (below the subgrade is a Portland cement concrete slab), the effect of moisture on the modulus of subgrade was not considered in this case. Meanwhile, for lacking of solar radiation, the temperature of pavement in laboratory does not vary in depth, so the temperature measured at the middle depth of the asphalt layer was used as representative temperature. After temperature correction, deflection measured at different temperature was utilized for regression purpose in the later analysis. With respect to deflection measured in field, when paving these test sections, in order to remove the effect of environment, a waterproof fabric was placed on the top of the subgrade. Moreover, as to the back-calculated modulus from ABAQUS, its variation with time was very small, so the deflection measured just after the completion of the test section was included in this paper to build the F formula. Table 3 shows the parameters used for building F. Table 4 is the result calculated from Table 3.

Table 3: Calculation of key influence factors

| Structure number | $l_{theory}$(0.001mm) | $E_0$(MPa) | $E_{Xsurface}$(MPa) | $h_{Xsurface}$(m) | $E_{Xbase}$(MPa) | $h_{Xbase}$(m) |
|---|---|---|---|---|---|---|
| L-1 | 86.9 | 107 | 7844 | 0.2 | 13315 | 0.2 |
| L-2 | 70.1 | 110.5 | 7044.6 | 0.1 | 10579.5 | 0.393 |
| L-3 | 218.5 | 69 | 7044.6 | 0.1 | 6832.5 | 0.275 |
| I-1 | 146.5 | 166 | 6245.6 | 0.05 | 11058.7 | 0.321 |
| I-2 | 154 | 168 | 6245.6 | 0.1 | 10023.5 | 0.287 |
| I-3 | 291.7 | 164 | 6245.6 | 0.15 | 273.3 | 0.33 |
| I-4 | 183.3 | 165 | 6245.6 | 0.15 | 3476.5 | 0.21 |
| I-5 | 202 98 | 6245.6 | 0.05 | 11058.7 | 0.321 | |
| I-6 | 210.5 | 100 | 6245.6 | 0.1 | 10023.5 | 0.287 |
| I-7 | 382.4 | 96 | 6245.6 | 0.15 | 273.3 | 0.33 |
| I-8 | 249.1 | 97 | 6245.6 | 0.15 | 3476.5 | 0.21 |

$l_{theory}$-theoretically calculated deflection

Table 4: Result of Deflection Synthetic Correction coefficient F

| Structure | Temperature (℃) | Deflection synthetic correction coefficient, F | | | Variation coefficient (%) |
|---|---|---|---|---|---|
| | | MIN | MAX | MEAN | |
| L-1 | 10.3～11.1 | 0.93 | 1.23 | 1.14 | 5.87 |
| L-2 | 10.9～11.9 | 0.93 | 1.17 | 0.99 | 8.54 |
| L-3 | 11.9～12.3 | 1.06 | 1.47 | 1.35 | 9.68 |
| I-1 | 8.6 | 0.97 | 1.21 | 1.06 | 11.12 |
| I-2 | 8.6 | 0.83 | 1.24 | 1.19 | 12.13 |
| I-3 | 8.6 | 0.79 | 0.96 | 0.89 | 9.94 |
| I-4 | 8.6 | 0.64 | 1.07 | 0.81 | 13.17 |
| I-5 | 8.6 | 1.15 | 1.55 | 1.42 | 10.12 |
| I-6 | 8.6 | 1.04 | 1.52 | 1.41 | 9.78 |
| I-7 | 8.6 | 0.76 | 1.36 | 1.1 | 9.06 |
| I-8 | 8.6 | 0.72 | 1.13 | 0.97 | 10.19 |

To construct the F formula, the form of F in latest design guide in China was referred, which is:

$$F = a\left(\frac{E_{Xsurface}}{E_{Xbase}}\right)^{b} h_X{}^{c} E_0{}^{d} \qquad (7)$$

To calibrate F, equation was taken logarithm both side, then F could convert into the form like:

$$Y = A + BX_1 + CX_2 + DX_3 \qquad (8)$$

In this case, F is converted into a multiple liner function. To fit F formula and calibrate the factors in equation (7), data analyzing program Origin v8.0 was included for multi linear regression. Table 5 shows the fitting results.

Table 5: Result of Regression analysis

| Equation number | *a* | *b* | *c* | *d* | Sample Size | $R^2$ | Residual | *F* statistic |
|---|---|---|---|---|---|---|---|---|
| Equation(8) | 0.2 | 0.386 | -3.569 | -0.433 | 60 | 0.854 | 0.034 | 14.65 |
| Equation(9) | 7.296 | -0.225 | -1.035 | -0.605 | 344 | 0.861 | 0.071 | 15.55 |

Equation (8) in Table 5 is applicable to pavement with only granular base, and equation (9) is built for pavement with chemical treated base or asphalt treated base. As table 5 indicates, the correlation coefficient of both equation (8) and (9) are greater than 0.85 which insured a good fitting. Equation (8) and (9) told that deflection synthetic correction coefficient F decreases with the increase of thickness and modulus of subgrade. For granular base asphalt pavement, the ratio of surface layer (asphalt layer) and base is greater than 1, F increases with the increase of this ratio. However, for chemical treated base, this ratio is less than 1, F decreases with the increase of the ratio. For these two kinds of pavement, when the stiffness of layers was uniformly distributed, the difference between theoretically calculated deflection and measured deflection is very small (F close to 1), then deflection does not need correction any more.

## 5 VERIFICATION OF F FORMULA

To verify the feasibility and applicability of F formula, the data collected in 6 freeways in China were used.

Table6: Verification of F formula

| Defelction | G25 | | | | | G5001 | G22-JL | G15 | G22-ML | G2001 |
|---|---|---|---|---|---|---|---|---|---|---|
| | S1 | S2 | S3 | S4 | S5 | | | | | |
| $l_{theory}$(0.001mm) | 117.4 | 127.6 | 154.8 | 84 | 87.9 | 92.11 | 131.5 | 138.8 | 149.5 | 135.5 |
| $l_s$(0.001mm) | 42.2 | 52.4 | 68.9 | 48.4 | 48.5 | 80 | 65.2 | 30.5 | 31 | 46.28 |
| Representative temperature(℃) | 12.77 | 12.31 | 11.98 | 12.15 | 10.57 | 29 | 10.5 | 3.8 | 4 | 10.2 |
| $l_{corrected}$(0.001mm) | 51.4 | 60.3 | 89.5 | 42.2 | 67.3 | 82.83 | 83.3 | 46.3 | 46.4 | 59.6 |

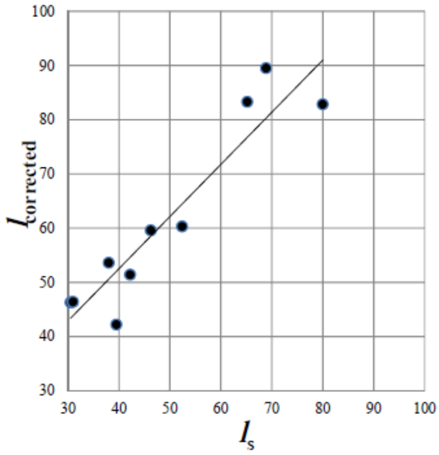



Figure 4: measured deflection vs. corrected deflection (0.001mm)

Both Table6 and figure 4 indicates, F formula has good applicability in engineering practice and fits the deflection measurements well. The maximum relative error between corrected deflection and measured deflection is 34% (G15) which is much smaller than the gap in record; the application of F could short the gap between theoretical deflection and measured deflection efficiently. Four of five with large differences were from pavement with large deflection which indicates weak structure. However, to improve the accuracy of its prediction, more deflection tested from more pavement structures are needed.

## 6 CONCLUSIONS AND DISCUSSIONS

- By the development of UMAT in ABAQUS, a method for back-calculating the modulus of granular material was advanced.
- Through application of grey entropy method, the key influence factors, total thickness of pavement, H; modulus of subgrade, $E_0$; ratio of modulus of surface layer and base, $E_1/E_2$ were determined to construct the F formula.
- Through multi linear regression, the F formula was calibrated, the correlation coefficient of the two formulas are greater than 0.85, which indicate a good fitting.
- Verification by deflection collected from 6 freeways show that, the maximum relative error is 34%, which could shorten the gap between theoretical deflection and measured deflection efficiently. To improve the accuracy of the prediction, especially for weak pavement structure, more deflection and structures are needed to refine the formula.

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